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the Cosmically Depressed: Life, Sociology and Identity of Voids

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Abstract. In this contribution we review and discuss several aspects of Cosmic Voids, as a background for our Void Galaxy Survey (accompanying paper by Stanonik et al.). Following a sketch of the general characteristics of void formation and evolution, we describe the influence of the environment on their development and structure and the characteristic hierarchical buildup of the cosmic void population. In order to be able to study the resulting tenuous void substructure and the galaxies populating the interior of voids, we subsequently set out to describe our parameter free tessellation-based watershed void finding technique. It allows us to trace the outline, shape and size of voids in galaxy redshift surveys. The application of this technique enables us to find galaxies in the deepest troughs of the cosmic galaxy distribution, and has formed the basis of our void galaxy program.

1. Cosmic Depressions

Cosmic Voids have been known as a feature of galaxy surveys since the first surveys were compiled (Chincarini & Rood 1975; Gregory & Thompson 1978; Einasto et al. 1980). They are enormous regions with sizes in the range of $20 - 50h^{-1}$ Mpc that are practically devoid of any galaxy, usually roundish in shape and occupying the major share of space in the Universe. Forming a key component of the *Cosmic Web* (Bond et al. 1991), they are surrounded by elongated filaments, sheetlike walls and dense compact clusters. Following the discovery by Kirshner et al. (1981) of the most dramatic specimen, the Boötes void, a hint of their central position within a weblike arrangement came with the first CfA redshift slice (de Lapparent et al. 1986). This view has been dramatically endorsed and expanded by the redshift maps of the 2dFGRS and SDSS surveys (Colless et al. 2003; Tegmark et al. 2004). They have established voids as an integral component of the Cosmic Web. The 2dFGRS maps and SDSS maps are telling illustrations of the ubiquity and prominence of voids in the

cosmic galaxy distribution. There are a variety of reasons why voids are cosmologically interesting. They are a prominent aspect of the Megaparsec Universe, instrumental in the spatial organization of the Cosmic Web. They also contain a considerable amount of information on the underlying cosmological scenario and on global cosmological parameters (e.g. Ryden & Melott 1996; Park & Lee 2007; Lavaux & Wandelt 2009). A final important aspect is that the pristine low-density environment of voids represents an ideal and pure setting for the study of galaxy formation and the influence of cosmic environment on the formation of galaxies (e.g. Peebles 2001).

2. Void Life: Formation and Evolution

At any cosmic epoch the voids that dominate the spatial matter distribution are a manifestation of the cosmic structure formation process reaching a non-linear stage of evolution.

Voids emerge out of the density troughs in the primordial Gaussian field of density fluctuations. Early theoretical models of void formation concentrated on the evolution of isolated voids (Hoffman & Shaham 1982; Icke 1984; Bertschinger 1985; Blumenthal et al. 1992). As a result of their underdensity voids represent a region of weaker gravity, resulting in an effective repulsive peculiar gravitational influence. Initially underdense regions therefore expand faster than the Hubble flow, and thus expand with respect to the background Universe. As voids expand, matter is squeezed in between them, and sheets and filaments form the void boundaries. This view is supported by numerical studies and computer simulations of the gravitational evolution of voids in more complex and realistic configurations (van de Weygaert & van Kampen 1993; Colberg et al. 2005).

3. Void Sociology

Computer simulations of the gravitational evolution of voids in realistic cosmological environments do show a considerably more complex situation than that described by idealized spherical or ellipsoidal models (van de Weygaert & van Kampen 1993; Colberg et al. 2005). In recent years the huge increase in computational resources has enabled N-body simulations to resolve in detail the intricate substructure of voids within the context of hierarchical cosmological structure formation scenarios. They confirm the theoretical expectation of voids having a rich substructure as a result of their hierarchical buildup (see e.g. fig. 3.).

It leads to a considerably modified view of the evolution of voids. One aspect concerns the dominant environmental influence on the evolution of voids. To a large extent the shape and mutual alignment of voids is dictated by the surrounding large scale structure and by large scale gravitational tidal influences. Equally important is the role of substructure within the interior of voids. This, and the interaction with the surroundings, turn out to be essential aspects of the *hierarchical* evolution of the void population in the Universe.

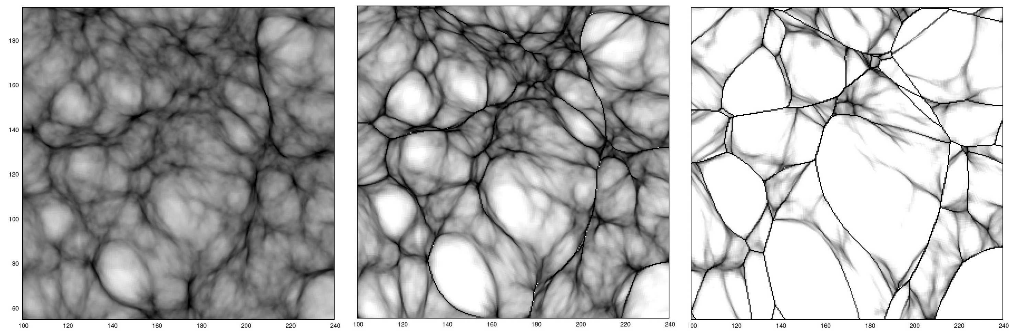

Figure 1. The evolution of cosmic structure according to the adhesion approximation (see text), in a 2-D (Eulerian) region of size $120h^{-1}$Mpc, at three different epochs. From left to right: a=0.15,0.30,0.70.

3.1. Environmentally Shaped, Tidally Directed

Icke (1984) pointed out that any (isolated) aspherical underdensity will become more spherical as it expands. In reality, voids will never reach sphericity. Even though voids tend to be less flattened or elongated than the halos in the dark matter distribution, they are nevertheless quite nonspherical. The flattening is a result of large scale dynamical and environmental factors (Platen et al. 2008). Even while their internal dynamics pushes them to a more spherical shape they will never be able to reach perfect sphericity before encountering surrounding structures such as neighbouring voids, overdense filaments and planar walls. Even more important may be the fact that, for voids, external tidal influences remain important: voids will always be rather moderate densities perturbations since they can never be more underdense than $\delta = -1$. External tidal forces are responsible for a significant anisotropic effect in the development of the voids. In extreme cases they may even cause complete collapse of the void.

3.2. Void Hierarchy: to Merge or to Collapse

In some sense voids have a considerably more complex evolutionary path than overdense halos. Many small primordial density troughs may exist within a larger underdense region. Their evolution, fate and interaction are key towards understanding the hierarchical buildup of the void network. Two processes dictate the evolution of voids: their *merging* into ever larger voids as well as the *collapse* and disappearance of small ones embedded in overdense regions. By identifying and assigning critical density values to the two evolutionary void processes of merging and collapse, Sheth & van de Weygaert (2004) managed to describe the hierarchical evolution of the void population in terms of a two-barrier *excursion set* formulation (Bond et al. 1991), akin to the evolution of overdense halos. An important guideline to this was the heuristic void model simulations by Dubinski et al. (1993). A significant contribution for a proper theoretical insight into the unfolding void hierarchy is the theoretical void study by Sahni et al. (1994) within the context of a Lagrangian adhesion model description.

An impression of this complex lifeline may be obtained from the sequence of timesteps depicted in fig. 3.. The figure shows the emerging weblike structure in a ΛCDM universe, in Eulerian space, following the adhesion approximation. One may see how the initially intricate weblike network in the interior of the large central underdense region gradually disappears as voids merge while the internal boundaries gradually fade away. In particular near the boundaries of large voids we may see the second void process, that of collapse of voids. It manifests itself in the form of a shearing and squeezing of less prominent voids, as a result of the expansion of prominent neighbouring voids or of the tidally induced filamentary or planar collapse of the weblike mass concentrations at edges of the voids.

The merging of subvoids within a large void's interior usually follows the emergence of these small-scale depressions as true voids. Once they do, their expansion tends to slow down. When the adjacent subvoids meet up, the matter in between is squeezed in thin walls and filaments. The peculiar velocities perpendicular to the void walls are mostly suppressed, resulting in a primarily tangential flow of matter within their mutual boundaries and the gradual fading of these structures while matter evacuates along the walls and filaments towards the enclosing boundary of the emerging void (Dubinski et al. 1993). The final result is the merging and absorption of the subvoids in the larger void which gradually emerges from their embedding underdensity. As far as the void population is concerned only the large void counts, while the faint and gradually fading imprint of the original outline of the subvoids remains as a reminder of the initial internal substructure.

The second void process, that of the collapse of mostly small and medium-sized voids, is responsible for the radical dissimilarity between void and halo populations. If a small scale minimum is embedded in a sufficiently high large scale density maximum, then the collapse of the larger surrounding region will eventually squeeze the underdense region it surrounds: small-scale voids will vanish when the region around them fully collapses. The manifest anisotropic shearing of collapsing voids near the boundaries of prominent voids (fig. 3.) is an indication for the important role of tidal forces in bringing about their demise.

3.3. Void Infrastructure

An important issue within the hierarchically proceeding evolution of voids and the Cosmic Web is the fate of its substructure. In voids the diluted and diminished infrastructure remains visible, at ever decreasing density contrast, as cinders of the earlier phases of the *void hierarchy* in which the substructure stood out more prominent

N-body simulations show that voids do retain a rich infrastructure. Examples such as the images of the Millennium simulation (Springel et al. 2005) show that while void substructure does fade, it does not disappear. We may find structures ranging from filamentary and sheetlike structures to a population of low mass dark matter halos and galaxies. Although challenging, these may also be seen in the observational reality. The galaxies that populate the voids do currently attract quite some attention (see next section). Also, the SDSS galaxy survey has uncovered a substantial level of substructure within the Boötes void.

4. In search of Voids

In order to be able to test theoretical predictions and compare them with the voids in observed reality, or those in the complex environment of N-body simulations, we need a strict and proper definition of a void. Voids are distinctive and striking features of the cosmic web, yet identifying them and tracing their outline within the complex geometry of the galaxy and mass distribution in galaxy surveys and simulations has proven to be a nontrivial issue. The watershed-based WVF algorithm of Platen et al. (2007) aims to avoid issues of both sampling density and shape. The WVF is defined with respect to the DTFE density field, assuring optimal sensitivity to the morphology of spatial structures and an unbiased probe over the full range of substructure in the mass distribution.

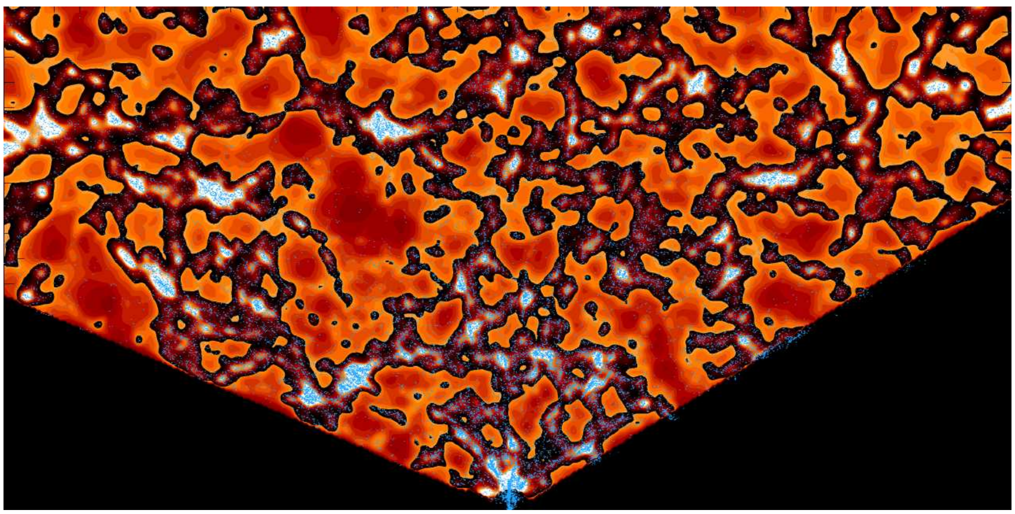

Figure 2. A visualization of the DTFE SDSS density field in a $12h^{-1}$ Mpc wide slice. The contour levels of the $1h^{-1}$ Mpc smoothed field are roughly divided between underdense and overdense regions. Galaxies are indicated by blue dots. Some of the most prominent features have been indicated: the *Boötes Supervoid* and the large supervoid identified by Bahcall & Soneira (1982). Also the large overdense *(Coma) Great Wall* and the *Hercules Supercluster* within this wall are indicated. From Platen 2009.

4.1. Tiling for Mapping: DTFE

When studying the cosmic matter distribution in the nearby Universe, the main source of information is that of the spatial location of galaxies. Also computer simulations of cosmic structure formation follow the evolving matter distribution by means of a large sample of discrete tracers, N-body particles. For the purpose of analyzing the topological intricacies of the cosmic web, and for tracibng the outline of voids and filaments, we have developed a technique based on a natural adaptive tiling of space defined by the sampling datapoints, be it galaxies or N-body particles.

The DTFE procedure, the Delaunay Tessellation Field Estimator (Schaap & van de Weygaert 2000; Schaap 2007; van de Weygaert & Schaap 2009), is based on the Voronoi

and its dual Delaunay tessellation (Okabe et al. 2000) in the survey/simulation volume. The method exploits the adaptivity of these tessellation cells to the local density and geometry of the generating spatial point process. The volume of the (contiguous) Voronoi cell around a sample galaxy is used as a zeroth order measure for the density at the location of the galaxy. The obtained density values are subsequently interpolated throughout the survey volume, using the Delaunay triangulation as the adaptive and irregular grid for a linear interpolation procedure.

In addition to the computational efficiency of the procedure, the density maps produced by DTFE have the virtue of retaining the anisotropic and hierarchical structures which are so characteristic of the Cosmic Web (Schaap 2007; van de Weygaert & Schaap 2009). The recent in-depth analysis by Platen (2009) has shown that for very large point samples, DTFE even outperforms more elaborate high-order methods with respect to quantitative and statistical evaluations of the density field. As a result, the DTFE density field can be used for objectively tracing structural features such as walls, filaments and voids. This is amply illustrated by the detailed map shown in fig. 4., showing the distribution of galaxies in a slice through the SDSS galaxy redshift survey.

4.2. A Watershed Search

When studying the topological and morphological structure of the cosmic matter distribution in the Cosmic Web, it is convenient to draw the analogy with a landscape. *Valleys* represent the large underdense voids that define the cells of the Cosmic Web. Their boundaries are *sheets* and *ridges*, defining the network of walls, filaments and clusters that defines the Cosmic Web.

A commonly used method in Image Analysis is the Watershed Transform (WST). It is a concept defined within the context of mathematical morphology, and was first introduced by Beucher & Lantuejoul (1979). It is widely used for segmenting images into distinct patches and features. The basic idea behind the WST stems from geophysics, where it is used to delineate the boundaries of separate domains, i.e. *basins* into which yields of e.g. rainfall will collect.

The word *watershed* finds its origin in the analogy of the procedure with that of a landscape being flooded by a rising level of water. Suppose we have a surface in the shape of a landscape, which is pierced at the location of each of the minima. As the water-level rises a growing fraction of the landscape will be flooded by the water in the expanding basins. Ultimately basins will meet at the ridges defined by *saddle-points* and *maxima* in the density field. The final result of the completely immersed landscape is a division of the landscape into individual cells, separated by the *ridge dams*.

The watershed transform was first introduced in a cosmological context as an objective technique to identify and outline voids in the cosmic matter and galaxy distribution (Platen et al. 2007; Platen 2009). Following the density field-landscape analogy, the Watershed Void Finder (WVF) method identifies the underdense void patches in the cosmic matter distribution with the watershed basins.

With respect to the other void finders the watershed algorithm has several advantages. The virtues of WVF may be appreciated from the comparison of its performance with a few other void finding algorithms in fig. 4.1. (from

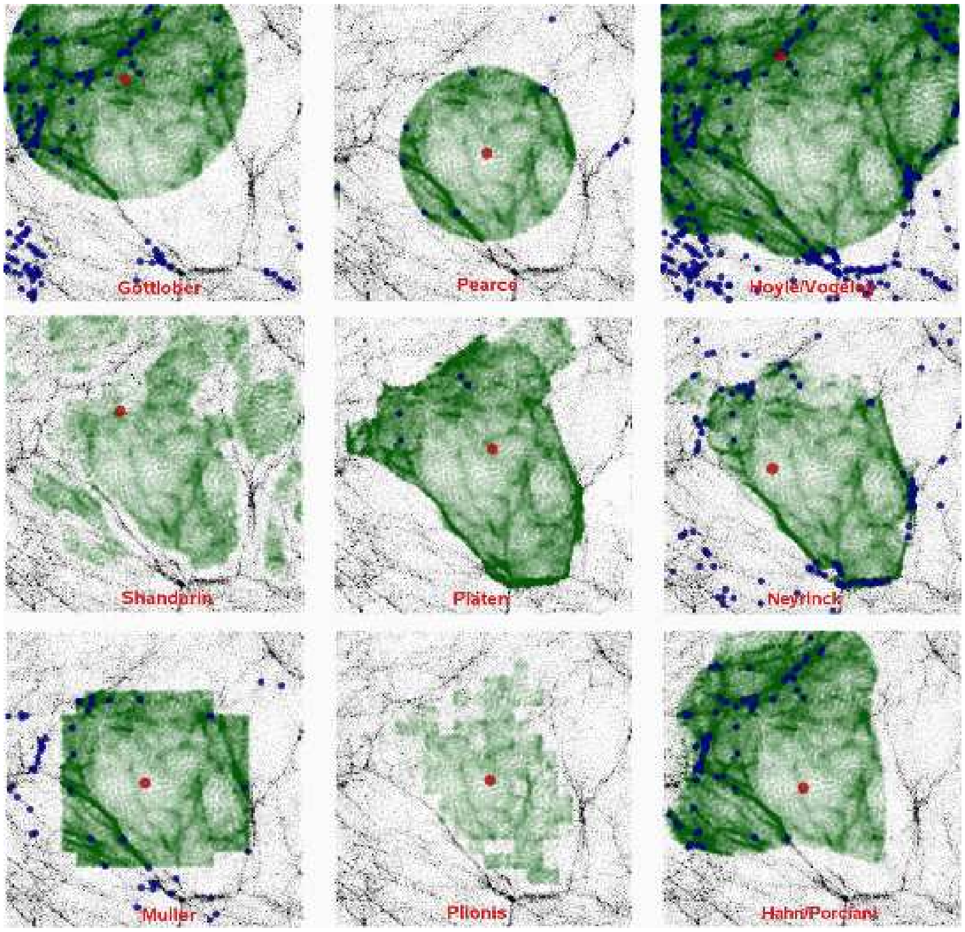

Figure 3. A compilation of void finders. The 9 frames illustrate the performance of different void finders with respect to a central voids in the milli-Millennium simulation. The N-body dark matter particles are depicted as black points. The blue dots locate (semi-analytically modelled) galaxies within the central void region. For each void finder, the identified void region is coloured green with the void centre marked by a red point. From Colberg et al. 2008.

Colberg et al. (2008)). The situation involves the region in and around a large void in the milli-Millennium simulation (Springel et al. 2005). Because it identifies a void segment on the basis of the crests in a density field surrounding a density minimum it is able to trace the void boundary even though it has a distorted and twisted shape. Also, because the contours around well chosen minima are by definition closed the transform is not sensitive to local protrusions between two adjacent voids. The main advantage of the WVF is that for an ideally smoothed density field it is able to find voids in an entirely parameter free fashion (in case there is noi noise in the data; in less ideal, and realistic, circumstances a few parameters have to be set for filtering out discreteness noise). Because the watershed works directly on the topology of the field, and does not involve a predefined geometry/shape. This is the reason behind one its main ad-

vantages, its independence of assumptions on the shape and size of voids [1]. The quoted vritues make WVF particularly suited for the analysis of the hierarchical void distribution expected in the commonly accepted cosmological scenarios.

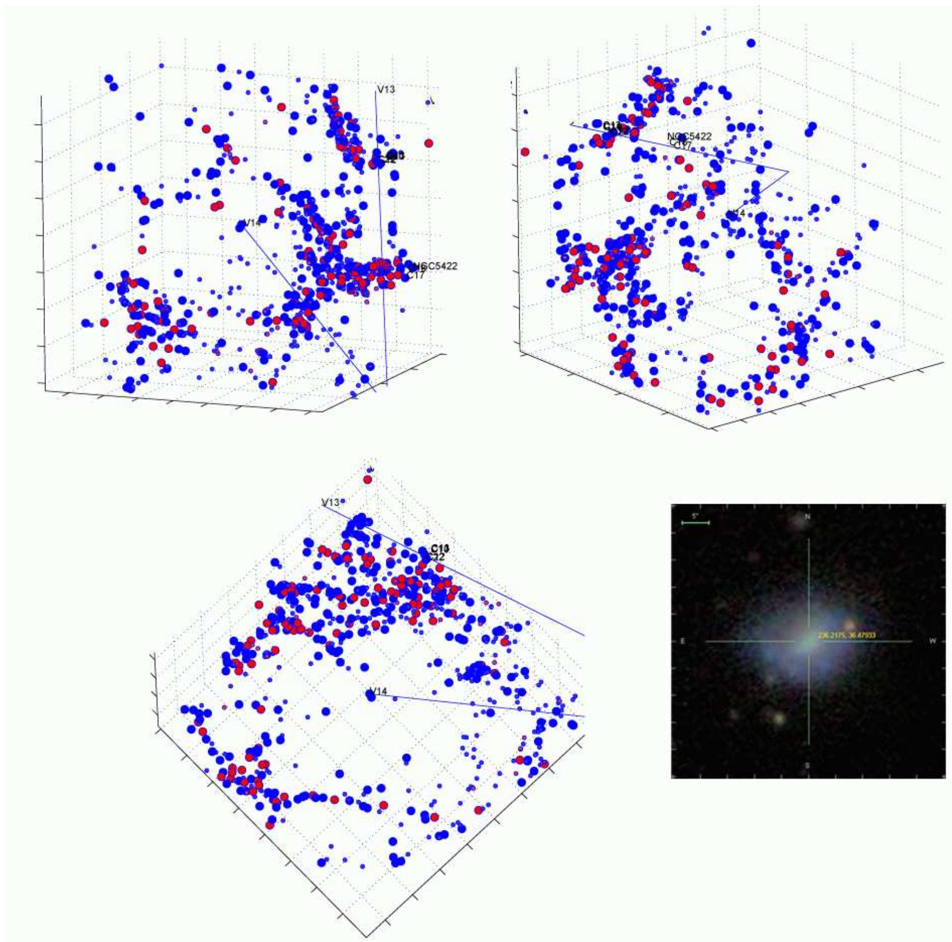

Figure 4. The SDSS galaxy distribution in and around the void in which void galaxy voidp14 of our void galaxy sample is located. Bright galaxies have large dots (B<-16), fainter ones are depicted by smaller dots. Redder galaxies, with g-r>0.6 are indicated by red dots.

5. Lonely Guards of the Cosmos: Void Galaxies

The pristine and isolated nature of the void environment represents an ideal setting for the study of galaxy formation. Largely unaffected by the complexities and processes modifying galaxies in high-density environments, the isolated void

[1] WVF shares this virtue with a similar tessellation-based void finding method, ZOBOV (Neyrinck 2008).

regions are expected to hold important clues to the formation and evolution of galaxies and our understanding of the environmental influences on galaxy formation. The presence and nature of void galaxies is also important for at least two additional reasons. The existence, or rather the apparent underabundance, of galaxies in the void regions may present a challenge for currently favoured galaxy formation theories (Peebles 2001). Interesting is also the extent to which galaxies trace substructure in voids. Such tenuous features would be fossil remnants of the hierarchical buildup of the Cosmic Web (Sheth & van de Weygaert 2004).

We have started a program to study the properties, the environment and their relationship of a complete sample of 60 void galaxies, probing a diversity in cosmic voids. The preliminary results of this campaign are described in the accompanying contribution by Stanonik et al. (also see Stanonik et al 2009a; Stanonik et al. 2009b). Our ability to outline voids in the SDSS galaxy distribution, by means of the WVF/DTFE procedure described in the previous section, has enabled us to identify a sample of galaxies which reside in the central and most underdense areas of cosmic voids. In summary, it allows us to find the emptiest regions and most lonely galaxies in the Local Universe. Upon having obtained the complete list of voids in the SDSS survey volume, and the void galaxies within their realm, we evaluate for each of the galaxies whether it conforms to a set of additional criteria. The galaxy should be

- located in the interior central region of clearly defined voids, if possible near the centre, and be as far removed from the boundary of the voids as possible.
- removed from the edge of the SDSS survey volume, as we do not wish to have galaxies in voids which extend past the edge of the SDSS coverage.
- be isolated (not a member of a group)
- not be within $\approx$ 750km/s from a foreground or background cluster. This assured us that the presence in a void of a galaxy could not be attributed to finger of god of god effect.
- for observational purposes , we prefer galaxies to be within a redshift $0.01 < z < 0.02$. It allows sufficient sensitivity and resolution of the gas structure and kinematics in the galaxies.

We also choose to select each sample galaxy to be in a different void. Note that there is no a priori selection on luminosity or colour of the void galaxies in our sample. The sample contains a representative number of early type galaxies.

A very nice example of the location of one of our void galaxies, nr. 14 in the pilot sample list, is shown in fig. 4.2.. It shows the SDSS galaxy distribution in and around the void in which the void galaxy (SDSS image included) is located. By showing the spatial galaxy distribution from three different perspectives, we seek to evoke a genuine three-dimensional impression.

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